

Racial/Ethnic Disparities in Nationwide PM_{2.5} Concentrations: Perils of Assuming a Linear Relationship

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Introduction

Ambient air pollution, including particulate matter <2.5 micrometers in aerodynamic diameter [fine particulate matter (PM_{2.5})], is a leading cause of morbidity and mortality in the United States.¹ The U.S. Environmental Protection Agency's (EPA) National Ambient Air Quality Standard for PM_{2.5} (2022 annual standard = 12 µg/m³) has resulted in consistently declining levels over the past decades but has not benefited racial/ethnic groups equally.^{2,3}

The United States has a history of environmental injustice, and studies from the 1980s through the present document racial/ethnic disparities in air pollution exposure.^{4–6} These studies have generally quantified disparities using population-weighted averages,^{2–4} with a handful additionally including linear regression estimates,^{7,8} which can adjust for known confounders. Population-weighted averages and linear regression models can mask the shape and magnitude of the relationship between racial/ethnic composition and ambient air pollution concentration. For example, as a result of zoning, racial segregation, and environmental racism, we might expect a 10% area-level increase in non-Hispanic Black individuals to be more strongly related to poor air quality in communities comprising 80–90% compared with communities comprising 30–40% Black residents. In this case, a linear model would yield a point estimate that respectively over- and underestimates the association at the lower and higher ends of the distribution.

Here, we explore departures from linearity in the relationship between racial/ethnic composition and PM_{2.5} concentration across the United States. We also quantitatively compare the strength of the nonlinear association to the linear one and highlight implications for the quantification of resulting racial/ethnic disparities.

Methods

Our analysis covered urban census tracts [$n = 58,030$ tracts contained within core-based statistical areas (CBSAs)] in the contiguous United States in 2010. We obtained modeled publicly available annual surface-level concentrations of PM_{2.5} for 2010 from a gridded (~1 × 1 km) data set,⁹ which we aggregated to census tracts. We compiled census tract-level percentage non-Hispanic Black and non-Hispanic White residents, percentage in poverty, and population density from the 2010 census.

We conducted descriptive analyses and evaluated the association between percentage racial/ethnic composition and PM_{2.5} concentration using linear mixed models with cubic natural splines whose number of degrees of freedom were selected with

the Akaike information criterion. We adjusted models for census tract-level poverty and population density and included state-specific fixed effects and CBSA-specific random intercepts. We also fit models with linear terms and calculated the bias in estimates had we used a linear PM_{2.5} term by subtracting the linear point estimate from the nonlinear one. All analyses were conducted with R (version 4.1.2; R Development Core Team).

Results and Discussion

Across 58,030 U.S. urban census tracts in 2010, the median percentages of non-Hispanic Black and non-Hispanic White residents were 4.6% and 69.7%, respectively. The highest percentage of non-Hispanic Black residents was found in tracts in the highest PM_{2.5} concentration quartiles (Table 1).

Linear and nonlinear models showed the same direction of association between racial/ethnic composition and ambient PM_{2.5} (positive for non-Hispanic Black and negative for non-Hispanic White) but different magnitudes across the distribution (Figure 1). For non-Hispanic Black residents, the linear model provided a point estimate of 0.09 [95% confidence interval (CI): 0.09, 0.10] µg/m³ for a 10%-point increase in percentage Black, which particularly underestimated the strength of this association in census tracts with a relatively small non-Hispanic Black population (Figure 1A). Using the nonlinear approach, moving from 0% to 10% and from 10% to 20% was respectively associated with a 1.11 (95% CI: 1.09, 1.14)-µg/m³ and a 0.008 (95% CI: 0.006, 0.010)-µg/m³ higher ambient PM_{2.5} concentration, which resulted in respective differences of 1.02 and –0.08 µg/m³ when comparing the linear point estimate to the nonlinear one. Similarly, for non-Hispanic White residents, the magnitude of difference between the linear and nonlinear point estimates substantially varied across the distribution (Figure 1B).

Most studies describe exposure disparities using population-weighted averages in agreement with our results: Non-Hispanic Black individuals were exposed to higher levels of PM_{2.5} compared with non-Hispanic White individuals.^{2–4,7} In 2010, 8.8% of the overall U.S. population lived in block groups where PM_{2.5} concentrations exceeded the 90th percentile; for the non-Hispanic Black population, this percentage grew to 16%.³ Jbaily et al.² expanded on previous studies that focused on population-weighted exposure at the extremes of the demographic distribution (i.e., the 10th and 90th percentiles).⁴ They estimated population-weighted averages across the distribution and documented a positive trend at the ZIP code–tabulation area level, which, in contrast to our findings, slightly strengthened at higher percentiles of non-Hispanic Black residents.² Liu et al. conducted a block group-level correlation analysis and found a positive unadjusted relationship between PM_{2.5} concentrations and the fraction of racial/ethnic minority residents.³ We build on these findings by *a*) modeling PM_{2.5} concentrations as a nonlinear function of proportion Black and White residents and *b*) accounting for poverty and population density. We found the steepest difference in PM_{2.5} concentrations for small variations in low percentages of Black residents.

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We declare no competing interests.

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Table 1. Distribution of 2010 U.S. Census tract-level non-Hispanic Black and non-Hispanic White percentages by quartiles of 2010 tract-level PM_{2.5} concentration across 58,030 urban census tracts located in core-based statistical areas.

Racial/ethnic percentages	PM _{2.5} quartiles (μg/m ³)			
	Q1 (1.75, 8.34) (n = 14,508)	Q2 (8.34, 9.87) (n = 14,506)	Q3 (9.87, 11.1) (n = 14,652)	Q4 (11.1, 16) (n = 14,362)
Black (%)				
Median	1.7	4.8	7.7	7.1
25th, 75th	0.7, 5.2	1.5, 14.4	2.3, 25.3	2.3, 27.2
10th, 90th	0.3, 13.7	0.6, 34.3	0.8, 68.9	0.9, 75.5
White (%)				
Median	78.2	72.4	65.6	55.9
25th, 75th	56.0, 89.6	46.3, 87.0	28.8, 84.6	17.6, 82.5
10th, 90th	27.0, 94.7	17.5, 93.7	5.4, 92.8	3.6, 92.1

Note: PM_{2.5}, fine particulate matter; Q, quartile.

Our method identified segments of the population for whom exposure has been substantially underestimated.^{7,8} Our results are not directly comparable to those of Jbaily et al.² and Liu et al.³ who did not model an association but, rather, likely differ because of *a*) our adjustment for known confounders, *b*) our restriction to urban areas, and *c*) differing spatial units of analysis. Future studies should investigate whether such nonlinear associations vary regionally or temporally or are modified by factors such as residential segregation.

Multiple studies confirm inequities in air pollution exposure by racial/ethnic group in the United States. However, standard linear models appear to substantially underestimate the relationship between race/ethnicity and PM_{2.5} in urban U.S. Census tracts with <10% non-Hispanic Black residents, which make up >65% of urban tracts. These results may reflect the policies implemented

due to relatively small increases in non-White populations, for example, racially restrictive zoning observed in the 1900s that may have resulted in disproportionate siting of industrial facilities or highways and rapid increases in air pollution.¹⁰ Our findings, combined with results indicating persistent,^{3,4} as well as increasing, disparities in exposures exceeding the U.S. EPA threshold,² highlight the importance of centering equity in air quality policy to address long-standing disparities.

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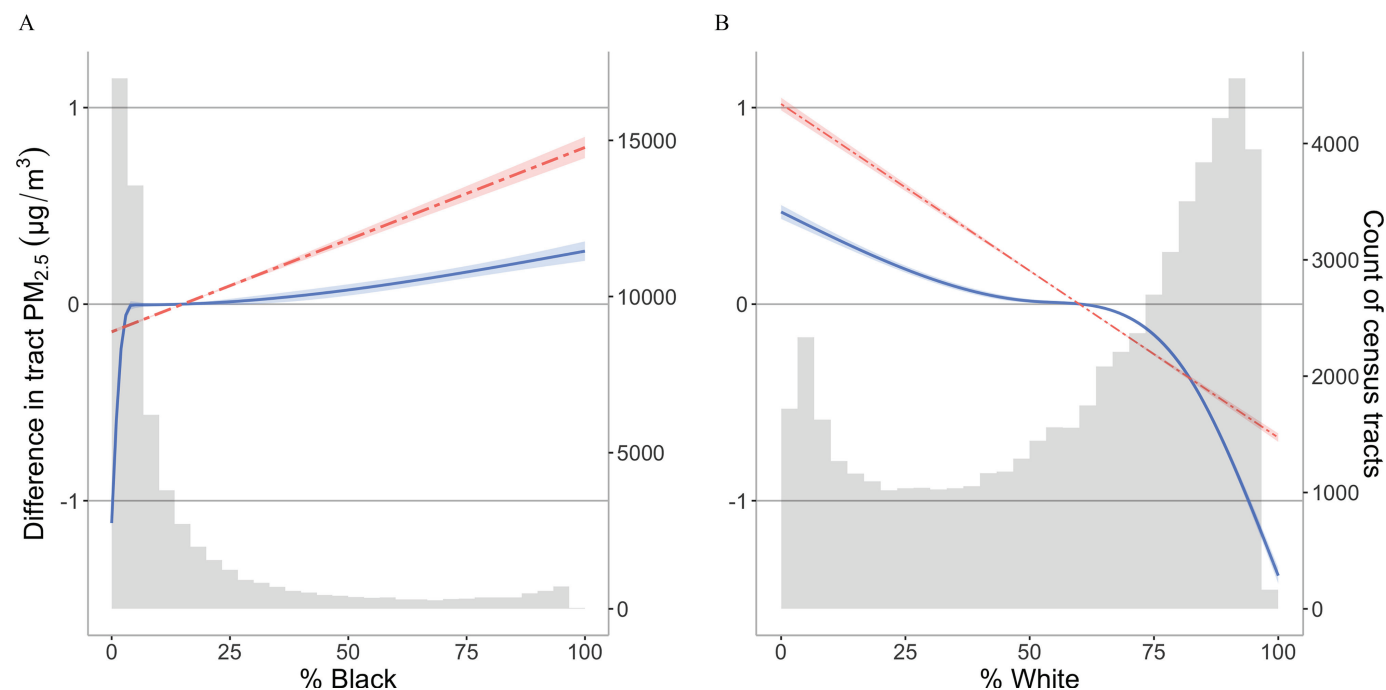


Figure 1. Difference in 2010 U.S. Census tract-level PM_{2.5} ($n = 58,030$) associated with increases in racial/ethnic group percentage [(A) Black; (B) White] relative to the mean percentage of that racial/ethnic group. This change was modeled linearly (dashed lines) and nonlinearly with cubic natural splines (solid lines). Models were adjusted for tract-level poverty (defined as percentage of individuals with income below the U.S. Census Bureau poverty threshold) and for population density (defined as number of people per kilometer squared). Both models included state-specific fixed effects and nonlinear models additionally included a CBSA-specific random intercept. The gray bars represent the distribution of percentage Black and White in urban U.S. Census tracts. Urban census tracts with <16% non-Hispanic Black residents make up 75% of urban census tracts. For non-Hispanic Black residents, in nonlinear models, moving from 0% to 10% and from 10% to 20% was respectively associated with a 1.11 (95% CI: 1.09, 1.14)-μg/m³ and a 0.008 (95% CI: 0.006, 0.010)-μg/m³ higher ambient PM_{2.5} concentration. The linear point estimate for a 10%-point increase in percentage Black was 0.09 (95% CI: 0.09, 0.10) μg/m³. For non-Hispanic White residents, in nonlinear models, moving from 70% to 80% and from 80% to 90% was associated with ambient PM_{2.5} concentrations that were respectively 0.23 (95% CI: -0.23, -0.22)-μg/m³ and 0.47 (95% CI: -0.47, -0.46)-μg/m³ lower. The linear point estimate for a 10%-point increase in percentage White was -0.17 (95% CI: -0.17, -0.16). Note: CI, confidence interval.

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